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Comparison of Designs For a 100 Foot Concrete Railway Arch Bridge

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COMPARISON OF DESIGNS FOR A 100-FOOT CONCRETE RAILWAY ARCH BRIDGE

...BY...

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THESIS FOR THE DEGREE OF BACHELOR OF SCIENCE
IN CIVIL ENGINEERING

COLLEGE OF ENGINEERING
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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

LAMBERT THEODORE ERICSON

ENTITLED COMPARISON OF DESIGNS FOR A 100-FOOT CONCRETE RAILWAY ARCH BRIDGE

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Bachelor of Science in Civil Engineering

Ira O. Baker.

HEAD OF DEPARTMENT OF Civil Engineering.

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INTRODUCTION.

It is the purpose of this thesis to determine whether it would have been more economical for the Peoria & Eastern Railway Co. to have constructed a single 100-foot span arch over the Vermillion River at Danville, than to have built the double 50-foot span arches now in place. It was the intention at first to design an arch whose span would be about 100-feet and whose unit stresses would not be greater than the unit stresses in the 50-foot arches. However, since the stresses in the 50-foot arches are comparatively small, and for other reasons to be stated later on, it was deemed advisable to design a 100-foot span arch which would be sufficiently strong to carry all the loading imposed upon it, but whose unit stresses were somewhat greater than those of the 50-foot arches. The problem in connection with the construction of the arch-bridge at Danville is a peculiar one on account of the extremely heavy dead load to be carried, in the shape of spandrel filling.

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The Vermilion River at this point was formerly crossed by a single-span deck-truss bridge, which had to be left in place until the new arch was finished. This limited the rise of the arch. It was the intention at the time of the construction to raise the grade line of the track twenty feet, making the base of the rail forty-five feet above the highest possible position of the crown of the arch. The filling over the arch is gravel, and is forty-five feet deep at the crown. The grade line is as yet unchanged, making the thickness of the filling above the crown twenty-five feet. However, the analysis which is to follow will be made according to the first assumption.

I. INVESTIGATION OF 50FT. ARCH

Analysis of Stresses

The analysis was made according to the elastic theory, as expounded by Cain, the arch being considered as consisting of homogeneous concrete.

1. Loading. The loading consists of forty-five feet of gravel filling over the crown of the arch and a live load over one half of the arch equivalent to four feet of gravel filling. The weight

of the gravel filling is assumed as 140 lb. per cu. ft. in all of the following computations, although the Peoria & Eastern Railway Co. considered the weight as being only 100 lb. per cu. ft. On account of the great depth of gravel filling, the concentrated live loads will be distributed evenly over nearly the whole arch, and their effect on the stresses produced will be very slight.

2. Stresses. The loading and stress diagrams are shown on Plate 2. Since the arch is of homogeneous concrete, the neutral axis coincides with the center-line of the arch-ring. The neutral axis was subdivided in such a way that the length of any division of the arch-ring, divided by the moment of inertia of that division, is constant; i.e., $\frac{s}{I}$ is constant or $\frac{s}{d^3} = \frac{s_1}{d_1^3}$, where s = length of each division, I = moment of inertia of the section, and d = radial depth. After the lengths $s_1, s_2, \ldots$ had been laid off in succession along the center-line of the arch-ring from either springing-line to the crown, the centers of these divisions were found, and were marked $a_1, a_2, \ldots$ beginning at the right-hand springing-line as shown on the stress sheet. Vertical lines were

drawn through $a_1, a_2, \ldots$ and the areas between these lines, the extrados and the upper limit of the spandrel filling, were computed. Multiplying these areas by the weight per cu. ft., determined the loads $P_1, P_2, \ldots$, which were laid off consecutively, midway between the points $a_1, a_2, \ldots$. At the crown the load coming between a_{14} and the crown was laid off midway between the two. These loads correspond to a section of the arch one-foot wide.

The loads $P_1, P_2, \ldots$ were then laid off to a scale of loads on a vertical line to the left and a horizontal thrust of 100,000 lb. at the crown was assumed. The right-hand part of the arch may be assumed to be taken away and the remaining portion would be held in that position by this horizontal thrust. The assumed horizontal thrust was laid off from the lower end of P_{14} on a horizontal line to fix the trial pole.

The equilibrium polygon $b_1, b_2, \ldots$ was then constructed in the usual manner and the line from $b_1 (= V_1)$ to $b_{28} (= V_{28})$ drawn. The sum of the ordinates from the line $V_1 V_{28}$ to the points $b_2, b_3, \ldots$ was measured to the scale of distance.

This sum is 309.65 ft-lb. and is called R. Regarding the ordinates as forces, the position of R was then found. It acts 0.106 feet to the left of AB.

The next step was to find a closing line mm_1, such that, if the ordinates from $V_1 V_{28}$ to mm_1 were treated as forces, their resultant would exactly equal R in magnitude and coincide with it in position. To this end a trial closing line mm_1 was first drawn and likewise the straight line $V_1 m$, dividing the ordinates into two sets. The resultant of those in one triangle was called Trial T and that in the other was called Trial T'. Drawing the line $m_1 n$, parallel to $V_1 V_{28}$, gives Trial T = Trial T'. They then act at the same distance from AB on opposite sides. Trial T = 140.4 ft-lb. and acts 6.75 feet to left of AB or 6.644 feet to left of R. With this data the closing line mm_1 was finally located by several steps explained in Caiss's Theory of Steel-Concrete Arches. The line KK' was then located in a similar manner with respect to the points $a_1, a_2, \ldots$ on the central line of the arch ring. This was done by measuring the ordinates $y_1, y_2, \ldots$ from the line OO_1 to $a_1, a_2, \ldots$ and dividing their sum by the number of ordinates, giving the distance, c = 6.95 feet, from the line OO_1 to the line KK'.

For the entire arch ring,

$$\Sigma kay = \Sigma (y-e)y = \Sigma y^2 - e\Sigma y = 186.9$$

$$\Sigma mby = 363$$

It is a principle of the equilibrium polygon that if the ordinates mb are altered in a given ratio, the pole distance is altered in the inverse ratio. The ordinates mb were altered in the ratio of 186.9 : 363.0 and the pole distance in the ratio of 363 : 186.9. To find the True Pole, a line parallel to m1n, was drawn from the Trial Pole to intersection with the load line. Then horizontally to the right of that point a length equal to the true pole distance was laid off. This true pole distance, measured to the scale of loads, gives the true horizontal thrust of the arch.

The new pole was thus found and the true equilibrium polygon for the arch, with the assumed loading, was then drawn in the arch ring in the usual manner. The points on the true equilibrium polygon in the same vertical with $a_1, a_2, \ldots$ are called $c_1, c_2, \ldots$ respectively. The center of pressure at the crown joint is similarly found. The true horizontal thrust of the arch is 194,000 lb.

The stresses due to temperature changes were figured, but they have been neglected in the analysis and design which follows. In nearly all concrete arches the tensile stresses which would be produc-

ed by a change in temperature of 100° F., as determined by computation, exceed the ultimate tensile strength of ordinary concrete. It would seem, therefore, that the concrete cannot be subject to a range of temperature even approximately as large as that of the atmosphere, or that some of the other assumptions or the methods of computations are in error. If such were not the case, many of the concrete arches now standing would have failed. Moreover, in the comparison under consideration it was not necessary to consider temperature stresses for the reason that the 100-foot span arch has a greater thickness than the 50-foot arches and would therefore be subject to a smaller range of temperature.

3. Unit Stresses due to dead and live loads. The unit stresses on the concrete at the extrados or intrados of any section are found by the equation:

$$S_1 = \frac{T}{A} \pm \frac{M v_1}{I} = \frac{T}{A} \pm \frac{M v_1}{\frac{1}{12} d^3},$$

where, S_1 = unit stresses in lb. per sq. ft.,
T = normal component of thrust,
A = area of section,
M = moment about centre of section = Hac,
V_1 = distance between the neutral axis and the line of the intrados or extrados,

I = moment of inertia of the section,
d = radial depth of the section.

TABLE I.

Stresses in 50-ft. Arch.

Joint	Stress in lb. per sq. in.	
	At Intrados	At Extrados
Crown	269	269
a_6	296	296
a_1	225	260

Contents and Cost.

These arches contain 17,617 cu. yds. of concrete. The total cost of concrete, excavation, and forms was about $112,053.00 This is equivalent to $6.36 per cu. yd. of concrete in place in the arch.

Proportions of Concrete.

American Portland Sandusky Cement was used. The concrete used in the arch ring was in the proportions of 1 cement, 2 sand, and 5 broken stone. For all other parts of the structure the concrete was made in the proportions of 1:3:6. All exposed surfaces were faced with mortar mixed in the proportions of 1 part cement to 2½ parts of sand.

Area of Waterway

There is an area of waterway equal to about 2550 sq. ft. The bed of the stream is about six feet below the springing line of the arch.

The Peoria & Eastern Ry. Co., in working out the thickness necessary at the crown and at the abutment, used Trautwine's empirical formula, taking into account the new fill of forty-five feet over the crown. They found by investigation that a foundation of shale could be had and the footings were made of a sufficient area to carry the load, which would be the contents of the arch at 140 lb. per cu. ft. and the earth fill at 100 lb. per cu. ft.

II. DESIGN OF 100-FT. SPAN ARCH.

By comparing results obtained from the use of different empirical formulae and by studying examples of arches now in existence, it was decided that a thickness at the crown of 8 feet would be sufficient. To obtain all the rise possible, the springing line was placed 3 feet lower than that in the 50-foot arches, making the rise at the crown 25 feet as before. The intrados was designed as an approximate ellipse, the length of the major axis being 100 feet and of the

minor axis 50 feet. The extrados was so designed that the projection of the radial depth, at any point, normal to the horizontal thrust, was equal to the crown thickness.

1. Loading. The loading in this arch was taken the same as that in the preceding case.

2. Analysis of Stresses. The stress sheet for this arch is shown on Plate 4. The method of obtaining the stresses is exactly similar to that given for the 50-foot arches.

The horizontal crown-thrust is 648,000 lb.

The stresses at different points in the arching are given in Table 2.

TABLE 2.

Stresses in 100 Ft. Arch.

Joint	Stress in lb. per. sq. in.	
	At Intrados	At Extrados
Crown	562	562
a_{21}	559	559
a_{26}	507	471
a_1	498	483

These stresses are considerably greater than those of the 50-foot arches, but are entirely safe. The actual stresses are not as great as those given, since the gravel filling does not weigh

140 lb. per cu. ft., as assumed, but weighs more nearly 100 lb. per cu. ft., as assumed by the Peoria & Eastern Ry. Co. There will also be some arch action developed by the filling and, in a short time after completion, there will be a considerable portion of the load whose weight will not be resting on the arch. On account of the small rise to be obtained in this case, it would require a crown thickness much greater than experience teaches us is necessary to have the stresses in this arch not exceed those of the 50-foot arches.

3. Abutments. The abutments were designed according to the article, Stability of Abutments, in Baker's Treatise on Masonry Construction. The horizontal unit-pressure at the abutment was considered as one-third of the vertical unit-pressure. The thickness at the springing line was made 25 feet. This thickness checked fairly well with several empirical formulae given in Trautwine's Pocket-Book.

4. Footings. A foundation of shale is to be had at this point. Since about the same vertical load load comes on the two abutments of this arch as on the two abutments and middle pier of the double arches, the area of the footings

in this arch was made practically the same as that in the double 50-foot arch. That makes each footing 30 feet wide at the bottom. A general plan of the arch, abutments, wing walls and coping is given on Plate 3.

5. Contents. The contents of the abutments below the springing in this arch are practically the same as the contents, below the same level, of the abutments and middle pier of the 50 foot arches. Since the contents of the wing-walls and coping do not necessarily depend upon the span of the arch, and since it is not known to the writer just how deep the footings go, the contents of the two arch-rings, above the level of the springing line of the 100-foot arch, will be compared. The contents of the arch-ring of the double 50-foot arches above this level is 4346 cu. yds., and of the 100-foot arch 5298 cu. yds.

6. Area of Waterway. The waterway given by this arch is about 2075 sq. ft. as compared with the 2550 sq. ft. given by the 50-ft. arches.

RESULTS SHOWN.

The results here given show that the double 50-foot arch in position at Danville, cost

less money than a single 100-foot span arch would have cost in the same position.

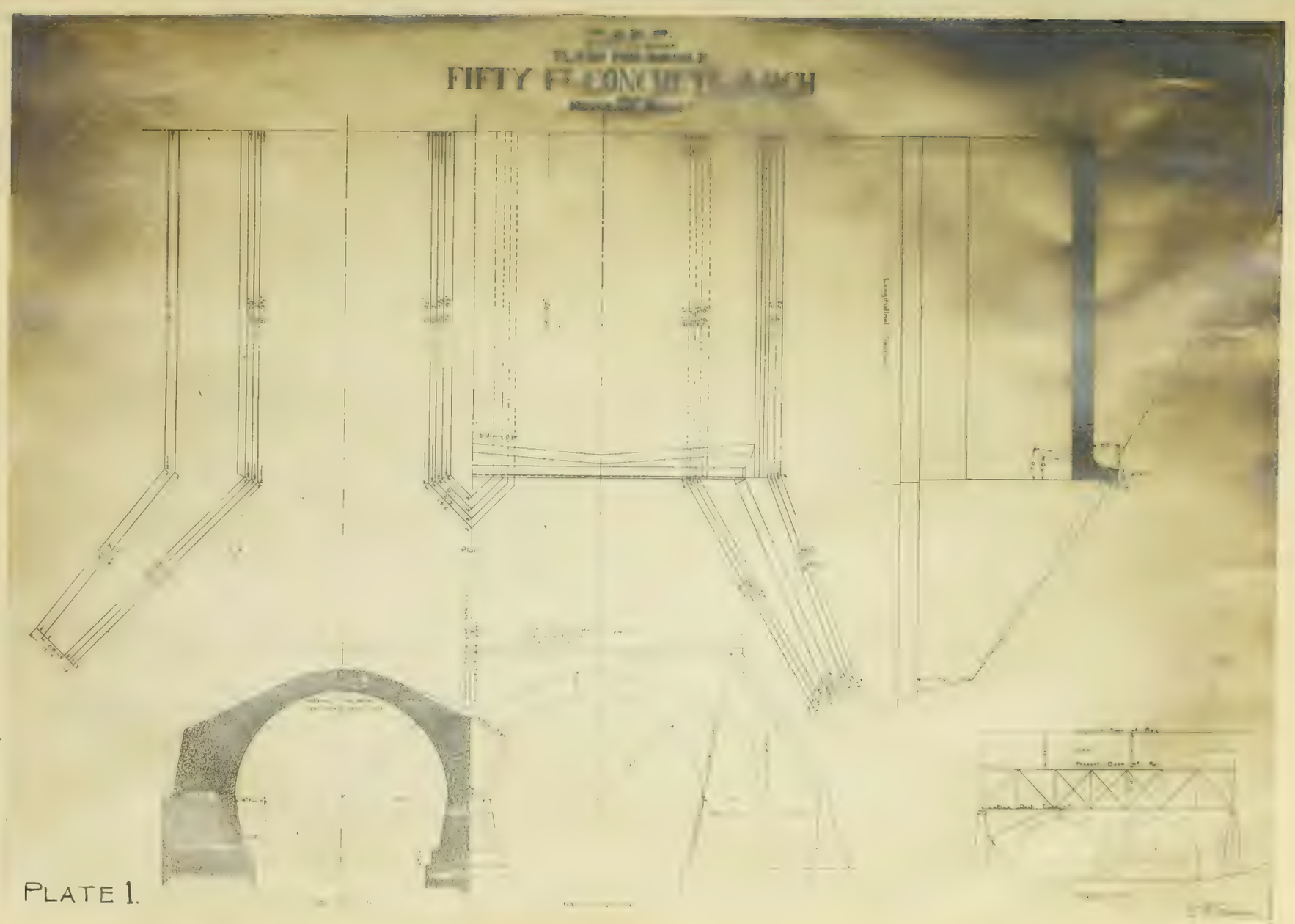


PLATE 1.

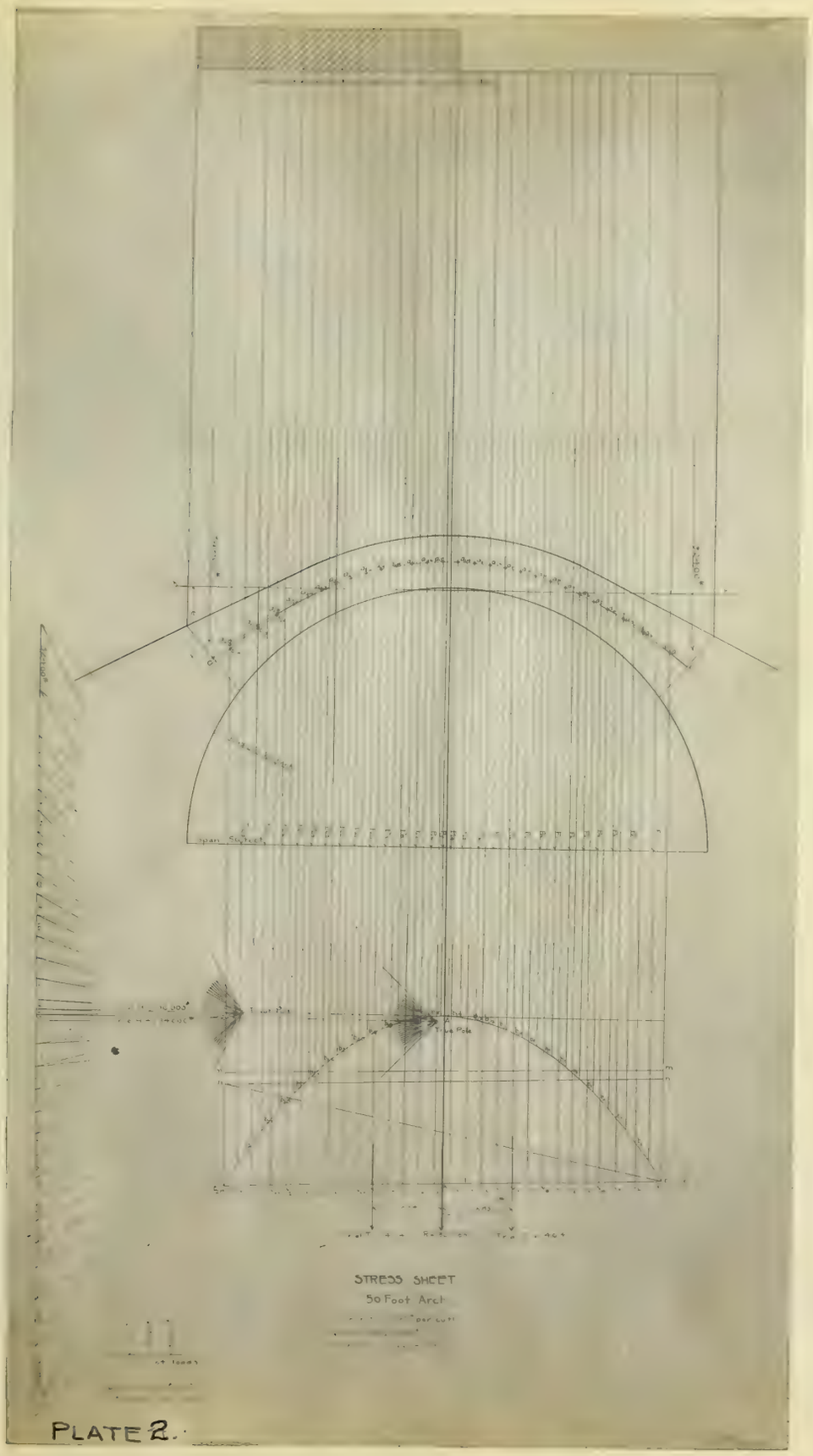
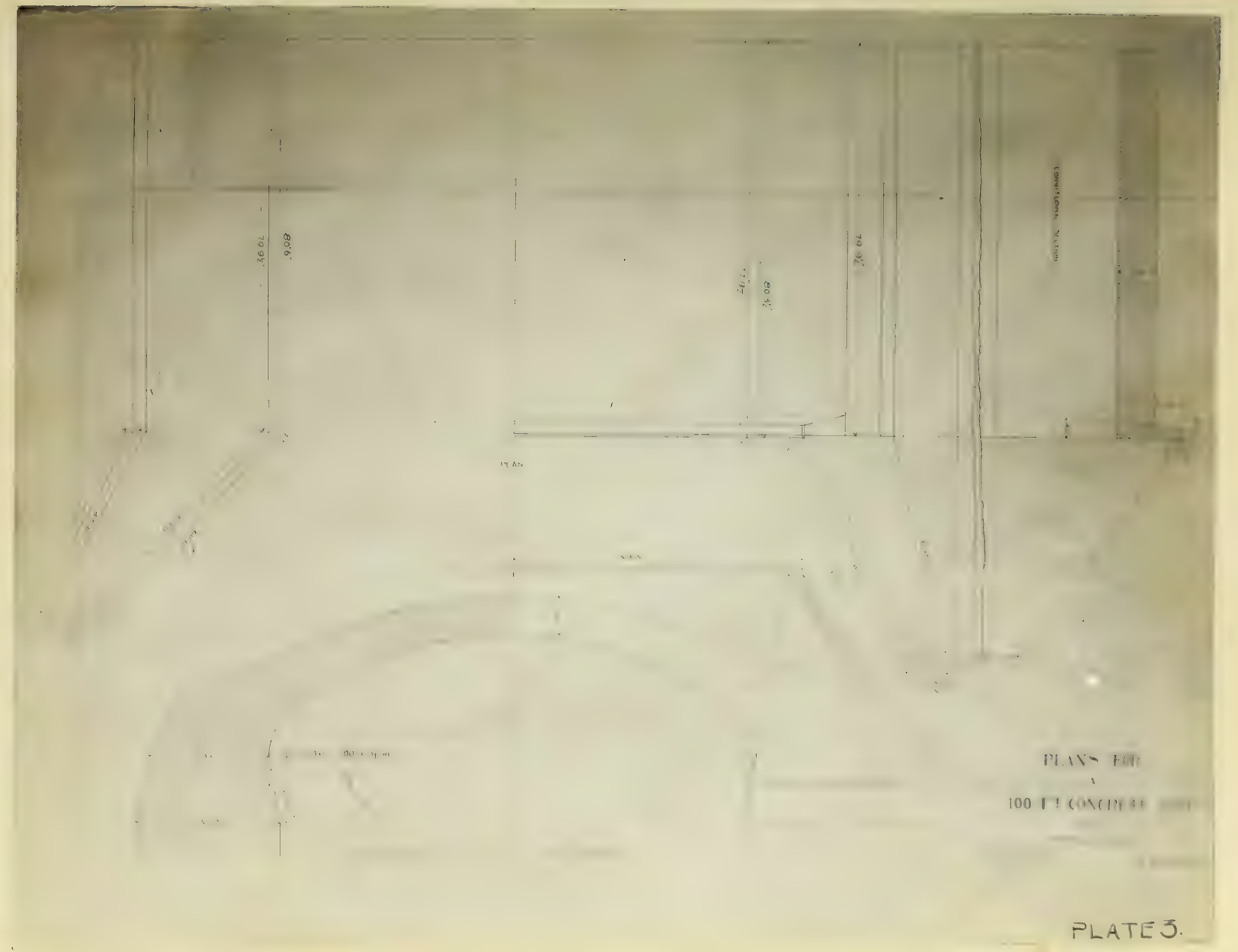


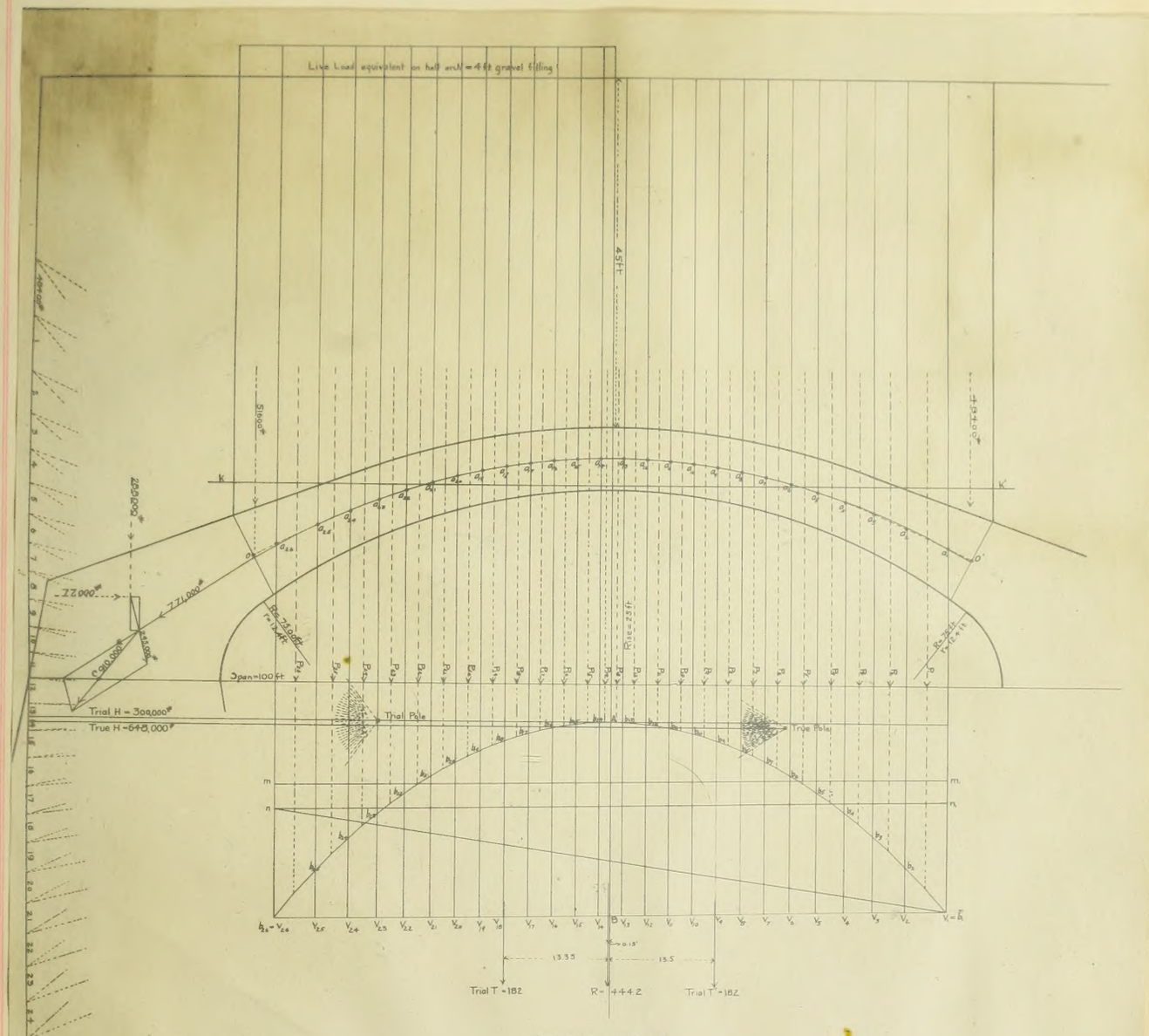
PLATE 2.



PLANS FOR

100 FT CONCRETE

PLATE 3.



STRESS SHEET

100 Foot Arch

Concrete = 140# per cu ft

Gravel Filling = 140# per cu ft

Crown Thickness = 8 ft

Scale of arch

Scale of loads

PLATE 4

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